Sustainable Wireless Information and Power Exchange for Energy-Constrained Communication Systems

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***Abstract*—This paper considers point-to-point wireless communications where an energy-constrained node, which has insufficient energy for data transmission, wants to exchange messages with a node with enough energy. In this system, we study power splitting (PS) based energy cooperation methods by exploiting wireless energy transfer techniques, and propose a new concept called *sustainable wireless information and power exchange* (SWIPE). In this SWIPE protocol, the node which has sufficient energy first transmits the information signal to the energy-constrained node. Then, the received signal at the energy-constrained node is utilized for both information decoding and energy harvesting via a PS circuit. At the consecutive time slot, by using the harvested energy, the energy-constrained node is now able to send a signal to the other node which employs a similar PS technique. This procedure continues by switching the operations of two nodes at each time slot. For the proposed SWIPE protocol, we present the optimal PS ratio computation algorithm in order to maximize the weighted sum throughput performance. Simulation results confirm the efficacy of the proposed SWIPE protocol over conventional schemes.**

I. Introduction

Wireless energy transfer (WET) methods utilizing radio frequency (RF) signals have been regarded as a promising solution for supplying power to electronic equipment. Recently, many literatures investigated the feasibility of applying the WET techniques to traditional communication systems where the role of the RF signals has been limited to wireless information transmission (WIT). In particular, simultaneous wireless information and power transfer (SWIPT) [1]–[6] and wireless powered communication network (WPCN) [7]–[11] have received great attentions.

The SWIPT systems mostly focus on a joint operation of the WIT and the WET over downlink networks, and have been dedicated to transceiver optimizations so that both information decoding (ID) and energy harvesting (EH) capabilities can be maximized. To perform the ID and the EH at the same time, time switching and power splitting (PS) receiver structures were introduced for the SWIPT in a two-user broadcast channel (BC) scenario [1]. After this pioneering work, these structures were extended to multi-user BC [2] [3], interference channels [4] [5], and relay networks [6]. Notice that the SWIPT is only interested in increasing the amount of the harvested energy but not in the usage of this energy.

Meanwhile, the WPCN systems investigate downlink WET and uplink WIT networks. Specifically, in the WPCN systems, an access point (AP) first broadcasts RF signals to charge energy-constrained nodes, and the harvested energy is used for WIT where the nodes transmit to the AP. The optimal resource allocation solutions were proposed for various single antenna WPCN in [7]–[9]. For multi-antenna WPCN systems, the optimal precoding matrix and the channel estimation procedures were presented in [10] [11]. Unlike the SWIPT systems, however, the WPCN does not allow the joint WIT and WET at the same time or over the same frequency band, and only considers the separated operation of information and energy transmission.

In this paper, we study a point-to-point wireless communication system where an energy-constrained node, which does not have enough energy for transmitting the RF signal, wants to exchange the information with the other node with sufficient energy. It is assumed that two nodes do not have any other external power supplies. Note that such devices prevail in sensor networks, device-to-device communications, and radio frequency identification (RFID) systems.

For this system, we propose a new concept called *sustainable wireless information and power exchange (SWIPE)*, which combines the SWIPT and the WPCN. In the proposed SWIPE protocol, the nodes switch their mode between a transmit mode and a receive mode, and thus at a given time, one node becomes a transmit node while the other node operates in a receive node. A transmit node radiates the information-bearing RF signal to a receive node which adopts the PS circuit. Then, the received signal can be split into an ID and an EH parts, and the harvested energy is stored at the receive node for future data transmission.

In the SWIPE methods, the node which has sufficient energy first operates in a transmit mode, whereas the energy-constrained node acts as a receive node. Then, at the consecutive time slot, the nodes switch their roles, i.e., the energy-constrained node now radiates the RF signal by using the energy harvested in the previous time slot, and the other node becomes a receive node which decodes information and collects energy from the received RF signal. Then, this procedure is repeated until the predefined communication time slots. It is worth noting that the proposed SWIPE is different from the WPCN where the joint transmission of information

This work was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (MSIP) of Korea Government under Grant 2014R1A2A1A10049769 and 2017R1A2B3012316. The work of K.-J. Lee was supported in part by Korea Electric Power Corporation (No. R17XA05-71) and Korea Evaluation Institute of Industrial Technology (KEIT) grant funded by the Korea government (MOTIE) (No.10079984, Development of non-binding multimodal wireless power transfer technology for wearable device).

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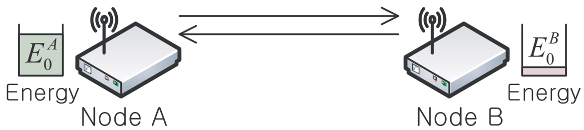


Fig. 1. Schematic diagram for energy-constrained point-to-point systems

and energy is not allowed. Also, since the harvested energy in the SWIPE is utilized for communications at future time slots, it differs from conventional SWIPT systems which only optimize the performance at the current time slot. Therefore, the proposed SWIPE protocol can be viewed as a general framework which includes the SWIPT and the WPCN as a special case.

To enhance the system performance of the proposed SWIPE protocol, we maximize the weighted sum throughput of two nodes by optimizing the PS ratio at each time slot. The globally optimal PS solution can be derived in a closed-form. Simulation results confirm that the proposed SWIPE protocol outperforms conventional systems without the SWIPE. Also, we show that the proposed PS solutions improve the weighted sum throughput performance over a naive PS solution.

The paper is organized as follows: In Section II, we introduce the system model and the novel SWIPE method. Section III presents the optimal PS algorithm. Section IV demonstrates the feasibility and the efficacy of the proposed SWIPE protocol through numerical results. Finally, the paper is terminated with conclusions in Section V.

II. System Model and Proposed SWIPE Protocol

In this section, we explain a system model for energy-constrained point-to-point communication in Fig. 1 where nodes A and B want to exchange their information with each other over orthogonal time resources. It is assumed that nodes A and B have an initial energy E_0^A and E_0^B, respectively, and are not equipped with any other external power supplies. In this configuration, node B is assumed to be energy-constrained, i.e., E_0^B is insufficient for transmitting the RF signals to node A, while the energy E_0^A at node A is enough for supporting node A's data transmission. For simplicity, we assume $E_0 \triangleq E_0^A > 0$ and $E_0^B = 0$.

When the data is exchanged between nodes A and B, we apply the PS techniques to both nodes, so that the received RF signal is decoupled into the EH and the ID parts. Note that in the conventional PS based SWIPT systems, the PS ratio, which indicates a portion of the received signal used for an EH, is normally designed to achieve the optimal tradeoff between the throughput performance and the amount of the harvested energy. In other words, the SWIPT does not consider the future usage of the harvested energy. However, in our scenario, the PS ratio should be determined such that data transmission performance at the current and future time is maximized. Thus, the conventional SWIPT cannot be directly applied to our system. Also, since joint transmission of the information and the energy is not allowed in the WPCN protocols, data transmission at node A is not viable with the WPCN. Thereby, in order to support interactive communications between two nodes, we need a new WET-enabled communication protocol which will be explained in the following.

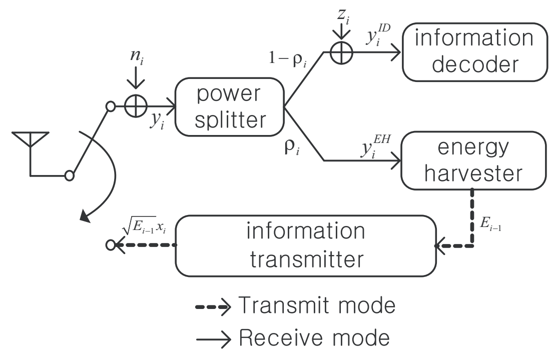


Fig. 2. Transceiver structure of the SWIPE nodes at time slot i

A. Sustainable Wireless Information and Power Exchange

In this subsection, we propose the SWIPE protocol which enables self-sustainable communications between nodes A and B. We consider a time-slotted system with total N time slots. For convenience, each time slot is assumed to have a unit length, and we interchangeably use the power and the energy terms throughout this paper. In the SWIPE, two nodes transmit and receive data with each other. We illustrate the tranceiver structure of the SWIPE nodes in Fig. 2 at a certain time slot i ($i = 1, \cdots, N$). A node in a transmit mode at time slot i sends the data symbol $x_i \sim \mathcal{CN}(0, 1)$ to the other node in a receive mode by using the energy E_{i-1} harvested in the previous time slot.[1] Then, the receive node at time slot i, which employs the PS ratio ρ_i as shown in Fig. 2, decodes information and harvests energy from the RF signal transmitted from the transmit node. In the subsequent time slot, the two nodes switch their role and continue the transmit and the receive operations. This process is repeated during N time slots. We summarize the operations of the proposed protocol at time slots i and $i+1$ with odd i in Fig. 3.

Now, let us detail the operations of the nodes at time slot i. Assuming frequency-flat quasi-static fading, the received signal y_i of the receive node at time slot i can be expressed as

$$y_i = \sqrt{E_{i-1}} h_i x_i + n_i,$$

where h_i accounts for the channel coefficient between two nodes at time slot i and $n_i \sim \mathcal{CN}(0, \delta^2)$ stands for the antenna noise at the receive node at time slot i.

In the meantime, the receive node divides the received signal y_i with the aid of the PS circuit which accepts the ρ_i portion of y_i for the EH and the remaining $1 - \rho_i$ portion for the ID. Then, the signals y_i^{EH} and y_i^{ID} for the EH and the ID operation at time slot i are respectively written by

$$\begin{aligned} y_i^{EH} &= \sqrt{\rho_i}(\sqrt{E_{i-1}} h_i x_i + n_i), \\ y_i^{ID} &= \sqrt{1-\rho_i}(\sqrt{E_{i-1}} h_i x_i + n_i) + z_i, \end{aligned} \tag{1}$$

[1] In this paper, we assume that the nodes employ a simple energy storage device such as a supercapacitor, and thus the harvested energy cannot be stored longer than one time slot. [7]. As a result, the transmit node consumes all the available energy E_{i-1} at each time slot i.

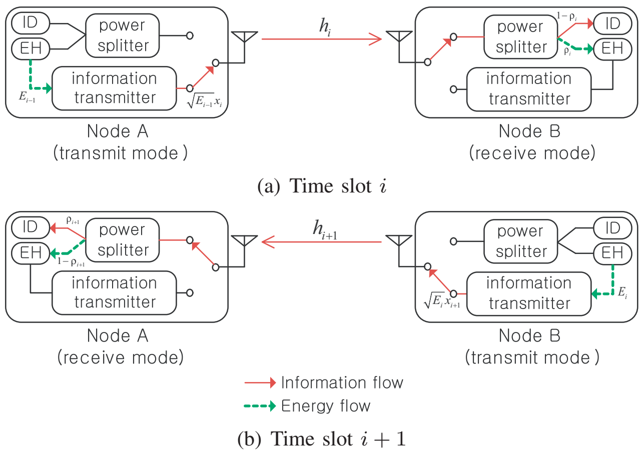


Fig. 3. Operations of each node in the proposed protocol at consecutive time slots i and $i+1$ with odd i

where $z_i \sim \mathcal{CN}(0, \sigma^2)$ equals the additive noise induced by the information decoding circuitry.

From (1), the harvested energy E_i of the receive node at time slot i is given by [1]

$$E_i = \eta \mathbb{E}_{x_i, n_i}[|y_i^{EH}|^2] \simeq \eta \rho_i E_{i-1}|h_i|^2 \quad (2)$$

$$= \eta^i E_0 H_i \prod_{j=1}^{i} \rho_j, \quad (3)$$

where $0 < \eta \leq 1$ is defined as the EH efficiency[2] $\mathbb{E}_X[\cdot]$ represents the expectation operation over a random variable X, and $H_i \triangleq \prod_{j=1}^{i} |h_j|^2$ denotes the product of the channel gains for time slots $1, \cdots, i$. In (2), we ignore the antenna noise power δ^2 since it is practically much smaller than that of the signal power [1]. Also, (3) comes from the recursive feature of $E_j = \eta \rho_j E_{j-1}|h_j|^2$ for $j = 1, \cdots, i-1$.

On the other hand, the achievable throughput R_i at time slot i can be obtained as

$$\begin{aligned} R_i &= \log_2\left(1 + \frac{(1-\rho_i)E_{i-1}|h_i|^2}{(1-\rho_i)\delta^2 + \sigma^2}\right) \\ &\simeq \log_2\left(1 + \frac{E_{i-1}|h_i|^2}{\sigma^2}(1-\rho_i)\right) \\ &= \log_2\left(1 + \frac{\eta^{i-1}E_0 H_i}{\sigma^2}(1-\rho_i)\prod_{j=1}^{i-1}\rho_j\right), \end{aligned} \quad (4)$$

where we assume $\delta^2 \ll \sigma^2$ in (4), i.e., the antenna noise n_i is negligible compared to the noise z_i introduced by the information decoding circuit, which is considered as the worst scenario for the PS receiver [1].

B. Problem Formulation

In this paper, we investigate the PS ratio optimization methods which maximize the weighted sum throughput performance $\sum_{i=1}^{N} w_i R_i$, where $w_i \geq 0$ indicates a given weight for time slot i. The weighted sum throughput maximization problem can be formulated as

$$\max_{\{\rho_i\}} \sum_{i=1}^{N} w_i \log_2\left(1 + \frac{\eta^{i-1}E_0 H_i}{\sigma^2}(1-\rho_i)\prod_{j=1}^{i-1}\rho_j\right) \quad (5)$$
$$s.t.\ 0 \leq \rho_i \leq 1, \text{ for } i = 1, \cdots, N.$$

It should be emphasized that the sum throughput maximization problem in (5) is a generalized framework which includes the SWIPT and the WPCN. Note that when $N = 1$, the proposed SWIPE reduces to the conventional SWIPT in which the PS ratio ρ_1 is designed such that both the throughput R_1 and the harvested energy E_1 can be maximized. Also, by setting $N = 2$, $\rho_1 = 1$, and $\rho_2 = 0$, the proposed protocol boils down to the conventional WPCN which does not support joint information and energy transfer at the same time. As a result, the sum throughput maximization problem in (5) for the proposed SWIPE protocol is totally different from existing WET-enabled wireless communication systems.

Problem (5) is non-convex in general, and thus it is not easy to obtain the optimal PS ratio solution $\{\rho_i^\star\}$. In the following section, we provide an efficient approach to optimally solve problem (5).

III. Optimal PS Ratio

In this section, we determine the global optimal solution for problem (5). By introducing auxiliary variables $A_i \triangleq \prod_{j=1}^{i} \rho_j$ for $i = 1, \cdots, N$, we reformulate the non-convex problem (5) into the equivalent convex problem as

$$\max_{\{A_i\}} \sum_{i=1}^{N} w_i \log_2\left(1 + \frac{\eta^{i-1}E_0 H_i}{\sigma^2}(A_{i-1} - A_i)\right) \quad (6)$$
$$s.t.\ A_i \geq A_{i+1}, \text{ for } i = 0, 1, \cdots, N, \quad (7)$$

where the constraint in (7) results from the definition of A_i with $A_0 \triangleq 1$ and $A_{N+1} \triangleq 0$.

One can check that problem (6) is convex and satisfies the Slater's condition, and thus the strong duality holds for this problem [13]. As a result, we can optimally solve (6) by applying the Lagrange duality method. The Lagrangian $\mathcal{L}(\{A_i\}, \{\nu_i\})$ of problem (6) is written by

$$\mathcal{L}(\{A_i\}, \{\nu_i\}) = \sum_{i=1}^{N} w_i \log_2\left(1 + \frac{\eta^{i-1}E_0 H_i}{\sigma^2}(A_{i-1} - A_i)\right) + \sum_{i=1}^{N}(\nu_i - \nu_{i-1})A_i + \nu_0,$$

where $\nu_i \geq 0$ equals the dual variable corresponding to the constraint $A_i \geq A_{i+1}$ for $i = 0, 1, \cdots, N$.

[2] In practice, the EH efficiency is a function of received power [12]. However, we assume that the EH efficiency is constant for simplicity [1]–[11].

Then, the Karush-Kuhn-Tucker (KKT) conditions can be expressed as

$$\nu_i^\star + \frac{w_{i+1}\eta^i E_0 H_{i+1}}{\sigma^2 + \eta^i E_0 H_{i+1}(A_i^\star - A_{i+1}^\star)}$$
$$= \nu_{i-1}^\star + \frac{w_i \eta^{i-1} E_0 H_i}{\sigma^2 + \eta^{i-1} E_0 H_i (A_{i-1}^\star - A_i^\star)}, \text{ for } i = 1, \cdots, N-1, \quad (8)$$
$$\nu_N^\star = \nu_{N-1}^\star + \frac{w_N \eta^{N-1} E_0 H_N}{\sigma^2 + \eta^{N-1} E_0 H_N (A_{N-1}^\star - A_N^\star)}, \quad (9)$$
$$\nu_i^\star (A_i^\star - A_{i+1}^\star) = 0, \text{ for } i = 0, 1, \cdots, N, \quad (10)$$

where $A_i^\star$ denotes the optimal primal variable with $A_0^\star \triangleq 1$ and $\nu_i^\star$ stands for the optimal dual variable. Note that (8) and (9) are derived from the zero gradient conditions $\frac{\partial \mathcal{L}(\{A_i\},\{\nu_i\})}{\partial A_i} = 0$, and (10) implies the complementary slackness conditions. By investigating the KKT conditions, the optimal solution $\{A_i^\star\}$ for problem (6) is presented in the following theorem.

Theorem 1: The optimal $A_i^\star$ for $i = 1, \cdots, N$ is obtained as

$$A_i^\star = \begin{cases} A_{i-1}^\star - \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}\right)^+, & \text{for } i = 1, \cdots, N-1, \\ 0, & \text{for } i = N, \end{cases} \quad (11)$$

where $(a)^+ \triangleq \max\{a, 0\}$, and the optimal dual variable $\nu_N^\star$ is given by a solution of the equation

$$\xi(\nu_N^\star) \triangleq \sum_{i=1}^{N} \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}\right)^+ = 1. \quad (12)$$

The optimal $\nu_N^\star$ satisfying (12) can be identified by the bisection method [13].

Proof: We first check (11) for $i = N$. The dual function $\mathcal{G}(\{\nu_i\})$ for problem (6) can be written by

$$\mathcal{G}(\{\nu_i\}) = \max_{\{A_i\}} \mathcal{L}(\{A_i\}, \{\nu_i\}). \quad (13)$$

It can be verified that $\nu_N^\star - \nu_{N-1}^\star$ must be positive, since otherwise the optimal $A_N^\star$ for problem (13) is calculated as $A_N^\star = -\infty$, which is infeasible for the primal problem (6). Therefore, it follows $\nu_N^\star > \nu_{N-1}^\star \geq 0$, i.e., the optimal dual variable $\nu_N^\star$ is positive. Combining this result and the complementary slackness condition $\nu_N^\star A_N^\star = 0$, the optimal $A_N^\star$ can be computed as $A_N^\star = 0$.

Next, we will prove (11) for $i = 1, \cdots, N-1$. From (8) and (9), we have

$$\nu_N^\star - \nu_{i-1}^\star = \frac{w_i \eta^{i-1} E_0 H_i}{\sigma^2 + \eta^{i-1} E_0 H_i (A_{i-1}^\star - A_i^\star)}, \text{ for } i = 1, \cdots, N. \quad (14)$$

Since $A_{i-1}^\star - A_i^\star$ is non-negative, the left-hand-side (LHS) of (14) should be greater than zero. Thus, (14) can be rewritten by

$$A_{i-1}^\star - A_i^\star = \frac{w_i}{\nu_N^\star - \nu_{i-1}^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}, \text{ for } i = 1, \cdots, N. \quad (15)$$

To solve the above N equations, we investigate two different cases of $\nu_N^\star < \theta_i$ and $\nu_N^\star \geq \theta_i$ with $\theta_i \triangleq \frac{w_i \eta^{i-1} E_0 H_i}{\sigma^2}$. First, when $\nu_N^\star < \theta_i$, it is easily shown that $A_{i-1}^\star - A_i^\star$ in (15) is positive since

$$A_{i-1}^\star - A_i^\star \geq \frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i} > 0,$$

where the first inequality comes from the dual feasible condition $\nu_{i-1}^\star \geq 0$. By combining this and the complementary slackness condition in (10), $\nu_{i-1}^\star$ becomes $\nu_{i-1}^\star = 0$. Therefore, $A_i^\star$ can be given by

$$A_i^\star = A_{i-1}^\star - \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}\right).$$

Second, we consider another case of $\nu_N^\star \geq \theta_i$. In this case, we will show $A_i^\star = A_{i-1}^\star$ by contradiction. Suppose that $A_{i-1}^\star - A_i^\star > 0$. Then, from (15), it follows

$$\begin{aligned} \nu_{i-1}^\star &= \nu_N^\star - \frac{\theta_i}{1 + \frac{\eta^{i-1} E_0 H_i}{\sigma^2}(A_{i-1}^\star - A_i^\star)} \\ &\geq \theta_i - \frac{\theta_i}{1 + \frac{\eta^{i-1} E_0 H_i}{\sigma^2}(A_{i-1}^\star - A_i^\star)} > 0, \end{aligned}$$

which violates the complementary slackness condition $\nu_{i-1}^\star (A_{i-1}^\star - A_i^\star) = 0$. As a result, the optimal $A_i^\star$ is obtained as $A_i^\star = A_{i-1}^\star$ in this case. Based on this analysis, it can be shown that the optimal $A_i^\star$ is calculated as in (11).

Now, we verify that the optimal dual variable $\nu_N^\star$ can be determined from (12). The function $\xi(\nu_N^\star)$ in (12) can be rewritten by

$$\begin{aligned} \xi(\nu_N^\star) &= \sum_{i=1}^{N} (A_{i-1}^\star - A_i^\star) && (16) \\ &= 1, && (17) \end{aligned}$$

where (16) comes from (11), and (17) is obtained by the definition $A_0^\star = 1$. Note that since the function $\xi(\nu_N^\star)$ is monotonically decreasing with respect to $\nu_N^\star$, we can identify the optimal $\nu_N^\star$ which fulfills $\xi(\nu_N^\star) = 1$ by using the bisection method [13]. This completes the proof. ■

Based on Theorem 1, we now proceed to derive an analytical expression for the optimal PS $\rho_i^\star$ of the original problem (5). Let us first define an integer L as

$$\begin{aligned} L \triangleq & \min_{1 \leq l \leq N} l && (18) \\ & s.t. \sum_{i=1}^{l} \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}\right)^+ = 1. \end{aligned}$$

In other words, L is the minimum time slot index l satisfying $\sum_{i=1}^{l} \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}\right)^+ = 1$.

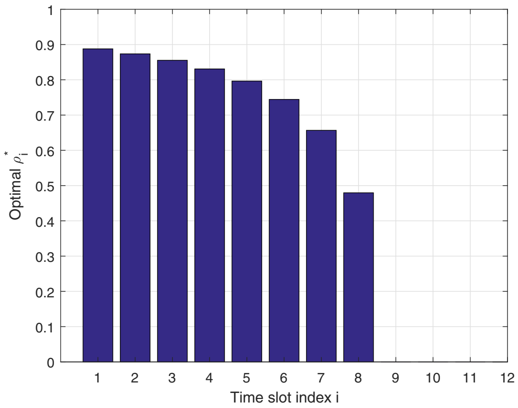
Then, it can be shown that $A_i^\star$ is positive for $i = 1, \cdots, L-1$ as

$$A_i^\star = 1 - \sum_{j=1}^{i} \left(\frac{w_j}{\nu_N^\star} - \frac{\sigma^2}{\eta^{j-1} E_0 H_j}\right)^+ > 0,$$

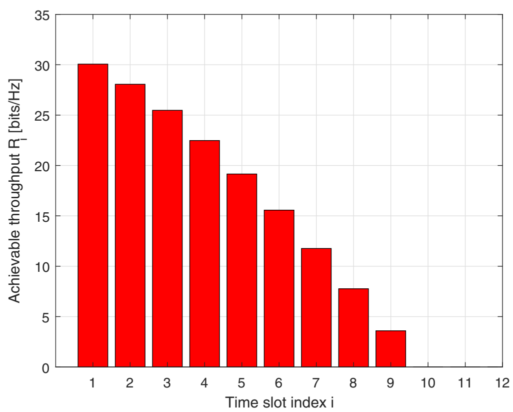
where the equality and the inequality are attained from (11) and the fact $\sum_{j=1}^{i} \left(\frac{w_j}{\nu_N^\star} - \frac{\sigma^2}{\eta^{j-1} E_0 H_j}\right)^+ < 1$, respectively. Hence, the optimal PS $\rho_i^\star$ for $i = 1, \cdots, L-1$ can be obtained as

$$\rho_i^\star = \frac{A_i^\star}{A_{i-1}^\star} = 1 - \frac{1}{\prod_{j=1}^{i-1} \rho_j^\star} \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i}\right)^+. \quad (19)$$

On the other hand, for $i = L, L+1, \cdots, N$, it can be shown from (18) that the equation $\sum_{j=1}^{i} \left(\frac{w_j}{\nu_N^\star} - \frac{\sigma^2}{\eta^{j-1} E_0 H_j}\right)^+ = 1$ is



(a) Optimal PS ratio $\rho_i^\star$



(b) Achievable throughput performance

Fig. 4. The optimal PS ratio and the throughput performance as a function of i for $N = 8$, $E_0 = 30$ dBm, $\sigma^2 = -70$ dBm

true since $\xi(\nu_N^\star) = 1$. As a result, the optimal $A_i^\star$ for $i = L, L+1, \cdots, N$ is given by $A_i^\star = 0$, and the thus optimal PS $\rho_i^\star$ for $i = L, L+1, \cdots, N$ should satisfy the following equations

$$A_i^\star = \prod_{j=L}^{i} \rho_j^\star \cdot \prod_{j=1}^{L-1} \rho_j^\star = 0. \tag{20}$$

Due to the fact $\rho_j^\star = \frac{A_j^\star}{A_{j-1}^\star} > 0$ for $j = 1, \cdots, L-1$, the optimal $\rho_i^\star$ for $i = L, L+1, \cdots, N$ satisfying (20) can be chosen as $\rho_i^\star = 0$. Finally, the optimal PS $\rho_i^\star$ for $i = 1, \cdots, N$ can be expressed by (21), shown at the top of the next page.

Now, we provide insights on the optimal PS ratio in (21). In Fig. 4, the optimal $\rho_i^\star$ and the achievable throughput performance R_i at each time slot i are plotted for $N = 12$, $E_0 = 30$ dBm, $\sigma^2 = -70$ dBm, $\eta = 0.5$, $w_i = 1$, and $H_i = \frac{1}{i}$, $\forall i$. It can be checked from Fig. 4 (a) that for $i \leq 8$, the optimal PS ratio is non-zero and decreases as the time slot index i grows, and then becomes zero after $i = 9$. Therefore, in this example, the time slot index L in (18) is given by $L = 9$.

From the plot, we can infer that for $i = 1, \cdots, L$, the nodes harvest non-zero energy in order to exchange their data at the future time slots, but the amount of the harvested energy gets smaller since the optimal $\rho_i^\star$ decreases. Eventually, at time slot L, the receive node no longer collects energy by setting $\rho_L^\star = 0$, and thus no energy is available for the remaining time slots $i = L+1, L+2, \cdots, N$. This is due to the fact that from the sum throughput maximization perspective, utilizing all the received signal power for the ID at time slot L is more beneficial than harvesting energy and transmitting data at the subsequent time slots. As a result, sustainable communications of two nodes are terminated at time slot L, and the throughput performance R_i for $i = L+1, L+2, \cdots, N$ is equal to zero as illustrated in Fig. 4 (b). For this reason, the time slot index L can be interpreted as a *terminating time slot* after which the SWIPE operation ends.

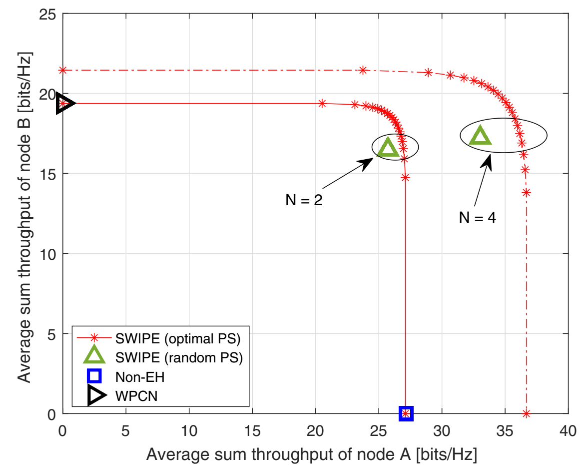


Fig. 5. Average sum throughput regions for $N = 2$ and 4 with $E_0 = 30$ dBm

To calculate the optimal PS in (21), we first need to identify the optimal dual variable $\nu_N^\star$ satisfying (12). Next, we can determine the terminating time slot L from (18). Finally, the optimal $\rho_i^\star$ can be computed by using the analytical expression in (21) for $i = 1, \cdots, L$. Note that the nodes no longer transmit after the terminating time slot L. The overall procedure for solving problem (5) is summarized below.

Algorithm 1. Proposed PS algorithm for the full CSI case
Compute $\nu_N^\star$ by solving (12) via the bisection method.
Find the time slot index L from (18).
Obtain the optimal PS $\rho_i^\star$ for $i = 1, \cdots, L$ from (21).

IV. Simulation Results

In this section, we present numerical results evaluating the performance of the SWIPE with the proposed optimal PS solution. For the simulations, we adopt the Nakagami-m fading channel model with $m = 5$ and 30 dB average signal attenuation between the nodes [8] [10], and we assume an antenna gain of 5 dBi at each node. Also, the noise variance σ^2 and the EH efficiency η are set to $\sigma^2 = -70$ dBm and $\eta = 0.5$, respectively.

In Fig. 5, the average sum throughput regions of the SWIPE protocol are presented for $N = 2$ and 4 with $E_0 = 30$ dBm. Here, the sum throughput R_A and R_B of node A and B are defined as $R_A = \sum_{i=1}^{N/2} R_{2i-1}$ and $R_B = \sum_{i=1}^{N/2} R_{2i}$,

$$\rho_i^\star = \begin{cases} 1 - \frac{1}{\prod_{j=1}^{i-1} \rho_j^\star} \left(\frac{w_i}{\nu_N^\star} - \frac{\sigma^2}{\eta^{i-1} E_0 H_i} \right)^+, & \text{for } i = 1, \cdots, L-1, \\ 0, & \text{for } i = L, L+1, \cdots, N. \end{cases} \quad (21)$$

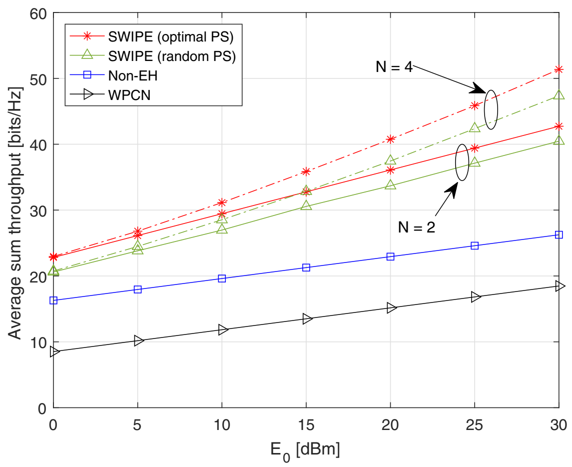


Fig. 6. Average sum throughput performance as a function of E_0 for $N = 2$ and 4

respectively. The sum throughput region can be generated from the proposed algorithm by setting the weights w_i for $i = 1, \cdots, N$ as $w_A = w_{2i-1}$ and $w_B = w_{2i}$, $\forall i$, with different combinations of w_A and w_B. For comparison, we also present the average sum throughput pair of the following three baseline schemes: the SWIPE with random PS scheme, non-EH, and the WPCN systems. In the random PS scheme, the proposed SWIPE adopts randomly selected PS ratios where ρ_i follows a uniform distribution over $[0, 1]$. The non-EH system stands for the conventional point-to-point communication without the EH techniques. Then, the communication between two nodes directly ends at the first time slot since node B does not have energy, i.e., the conventional non-EH scheme is a special case of the proposed SWIPE protocol with $N = 1$ and $\rho_1 = 0$. Also, in the WPCN, only the node B's information transmission is supported by setting $N = 2$, $\rho_1 = 1$, and $\rho_2 = 0$. From the curve of the SWIPE with proposed optimal PS solution, we can first see that the increased number of time slot N brings substantial sum throughput gains. In addition, the proposed PS optimization methods exhibit a larger sum throughput region than the baseline schemes which only achieve a single sum throughput pair. These observations verify that by utilizing the proposed SWIPE combined with the PS optimization method, we can significantly improve the data transmission throughput at both nodes.

Fig. 6 shows the average sum throughput performance as a function of the initial energy E_0 for $N = 2$ and 4. Here, the weight w_i is set to $w_i = 1$, $\forall i$. From the figure, it is observed that as the number of time slots N grows, the performance of the proposed SWIPE increases. Note that all the curves for the SWIPE outperform the conventional non-EH and the WPCN systems, which demonstrates the effectiveness of the proposed SWIPE. Moreover, it is shown that the SWIPE with the proposed optimal PS algorithms provides a 3 dB gain over the random PS scheme at $N = 4$.

V. Conclusion

In this paper, we have studied energy-constrained point-to-point wireless communication systems where an energy-constrained node wants to communicate with the other node which has non-zero energy. In this system, a new SWIPE protocol has been introduced which supports sustainable communications between two nodes with the aid of the PS based WET techniques. In order to maximize the weighted sum throughput performance of the SWIPE protocol, we have derived the globally optimal PS ratio solution in the closed-form expression. Simulation results have verified the performance gain of the SWIPE compared to the conventional non-EH and the WPCN systems.

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